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Congestion Control of High-Speed Networks

Columbia University
806 Schapiro CESPR
New York, N.Y. 10027

Summary

We report on four areas of activity in the past six months. These include, 1. work on the control of integrated video and image traffic, both at the access to a network, and within a high-speed network; 2. more general/game theoretic models for flow control in networks; 3. work on fault management for high-speed heterogeneous networks to improve survivability; 4. work on all-optical (lightwave) networks of the future, designed to take advantage of the enormous bandwidth capability available at optical frequencies

1. Control of Integrated Traffic

a. Access to Network

In the last six to nine months, we have been focusing on the integration of video and still image traffic in a broadband ATM type network. This work is an application of earlier work supported by the ONR grant on modeling video traffic behavior inside ATM multiplexers. We have formulated a framework for a control system which trades off performance requirements for the two types of traffic in order to improve network throughput. The control system has two levels: a burst level control which controls image traffic throughput using flow control, and cell level control which guarantees cell loss rate requirements for the two traffic classes. The burst level control takes advantage of the fact that still image traffic has less strict real time delays than video traffic, and, therefore, it can be delayed within reason during bursts of video traffic. The cell level control performs best effort buffer management to meet the cell loss requirements of each traffic class given the current load. The flow control guarantees that the probability the load leaves the feasible range of the cell level control is below a specified threshold.

We are in the process of writing a paper on the work described. This will also appear as a Chapter in a Ph.D. dissertation by Paul Skelly that is nearing completion. A paper on the earlier work on video has been submitted for publication [1].

Reference:

[1] Paul Skelly and Mischa Schwartz, "A Histogram-Based Model for Video Traffic Behavior in an ATM Multiplexer", submitted to IEEE/ACM Trans. on Networking.

b. Control within network

Networks of the future will support a wide range of services, each having its own Quality of Service (QOS) requirement at speeds that are magnitudes higher than in present day networks. This has created many new problems in the areas of Congestion Control and Traffic Management. To develop efficient control techniques we first need to have a sound understanding of the traffic characteristics throughout the network. Analytical modeling techniques used in the past to characterize traffic may not be useful anymore. This is especially true in the case of ATM, where, because of the fixed size cells, the output process is highly correlated to the arrival process, therefore to view the traffic at each node in the network independently (as has been done in the past) is unrealistic. Moreover the integration of video, voice, image, and data traffic, each with their own characteristics and QOS requirements, also make it unreasonable to use the models of the past. Using

simulations, one can model any type of network traffic, however simulations typically require a very long time to run, and are not accurate for small statistical values.

We first began by developing analytical expressions for QOS parameters such as probability of loss and buffer occupancy distributions for video over the entire network. To that end we generalized the Histogram decomposition technique to model video traffic over the network. We have also been able to analytically characterize different types of "smoothing" techniques which may be used in video to make the traffic more regular. We show that the "Deterministic Smoothing" technique is the optimal smoothing technique in terms of loss probabilities. We have also simplified our analysis and developed more efficient techniques to determine loss probabilities throughout the network when using deterministic smoothing at the source. Simulations have been used extensively to verify the analytical results, and close correspondence has been found. Currently, numerical results are being obtained on large networks to ensure the validity of the analysis, and to understand the effect on traffic which has progressed "deep" within the network.

We are also in the process of modeling still images such that we can analytically characterize the effect on traffic when they are superimposed with video. The next step will be to determine efficient scheduling and control techniques in the presence of integrated traffic such as image and video.

2. <u>Game theoretic models for flow control</u>

We have studied the existence of Nash equilibria of the flow control model introduced in [1], for a general product-form network where the monotonicity assumptions of that reference do not necessarily hold. Simple examples show that the joint strategy space--defined by the time-delay constraints of all users--does not satisfy the convexity condition posed by Rosen's theorem. Heuristics that incorporate the time-delay constraint of each user as a penalty component in its utility result in objective functions that either are not continuous, or do not satisfy certain second order monotonicity properties required by the standard equilibrium existence theorems (e.g., concavity in Rosen's theorem)

The performance objective of each user is to maximize its average throughput subject to an upper bound on its average time-delay. Previous attempts to study existence of equilibria for this flow control model were not successful, partly because the time-delay constraints couple the strategy spaces of the individual users in a way that does not allow the application of standard equilibrium existence theorems from the game theory literature.

To overcome these difficulties, we have taken a more general approach to the problem of equilibrium existence in noncooperative flow control algorithms. The concept of the reply correspondence of the underlying game plays a central role in this approach. Finding a noncooperative equilibrium of a decentralized control scheme ("game") amounts to solving a number of interdependent individual optimization problems simultaneously. Given a choice of strategies for all but one of the controllers, the set of optimal strategies for the remaining controller can be found. This way, a point-to-set correspondence, that maps the product strategy space of the game into itself, is defined. This is the best reply correspondence of the game. Any Nash equilibrium is a fixed point of this correspondence.

Instead of using standard game theoretic results that concentrate on the properties of the utility functions and the joint strategy space we focused on the best reply correspondence of the flow control game and examined the existence of fixed points of this correspondence From a technical standpoint, the merits of this approach are clear. The requirements in Rosen's theorem -- and other similar results from game theory -- guarantee that the best reply correspondence satisfies the sufficient conditions of some fixed-point theorem. Nevertheless, the best reply correspondence might satisfy these conditions, while the requirements on the utility functions and the joint strategy space are not met. Conceptually, on the other hand, the best reply correspondence is the natural representation of a decentralized control algorithm, for which objective functions or quality of service constraints might not even be explicitly defined.

For the investigated flow control model, the best reply correspondence was shown to be a function, implicitly defined by means of K interdependent linear programs. A definition of continuity for the set of optimal solutions of parametrized linear programs was introduced and, under appropriate conditions, it was shown that the best reply function is continuous. Brouwer's theorem implies, then, that the best reply function has a fixed point.

References:

[1] Hsiao, M.-T. and Lazar, A.A., "Optimal Decentralized Flow Control of Markovian Queueing Networks with Multiple Controllers", Performance Evaluation, Vol. 13, No.3, 1991, pp. 181-204.

[2] Korilis, I.A. and Lazar, A.A., "On the Existence of Equilibria for Noncooperative Flow Control", submitted for publication to the ACM Journal of the Association of Computing Machinery.

3. Fault management in high-speed networks

The new power brought with modern communication networks creates greater vulnerability. The trend toward a very large switch with a few strands of high speed fiber and more sophisticated software-controlled networks has increased concern about survivability for any single fault incident. At the same time, service disruption is no longer tolerated by industries because of increased need for network service by stock market operations, air-traffic control, and retailing, etc. Network Management has thus emerged as crucial for the successful deployment of a network. The International Organization for Standardization (ISO) and telecommunication industries are actively developing a set of comprehensive Network Management standards. It should be noted that network management standards address issues of syntax, modeling, and semantics of management information. OSI Network Management provides supporting mechanisms for management activity and does not explicitly define how a typical network management system should be designed. The standards are not concerned specifically with how, for example, faults are detected and identified. We hope to redress this situation and carry out work of a more fundamental nature, leading to a better understanding of the theoretical underpinnings of fault management.

In the work of [1] and [2], we propose to use a set of independent observers to detect faults in communication systems modeled by finite state machines. We give an algorithm for constructing these observers and a fast real-time fault detection mechanism for each observer. Since observers run in parallel and independently, an immediate benefit is graceful degradation - one failed observer does not cause the

fault management system to collapse. In addition, each observer has a simpler structure than the whole system and can be operated at higher speed. This approach can be used for fault management in high speed communication systems.

In the work of [3] and [4], we focus on probabilistic fault assessment for fault localization. We propose a framework for identifying most probable faulty network components from a set of generic alarms in a heterogeneous networking environment. Faults are treated as a loss of system connectivity due to malfunctions or breakdowns of network resources. A designated network entity, an entity with management responsibilities for instance, determines a fault has occurred when it is unable to communication with certain other entities. Given this information, as well as the information that it can communicate with another specified set of entities, a method based on maximum a posteriori (MAP) estimation is used to identify a ranked list of the most probable failed network resources.

References:

[1] C. Wang and M. Schwartz, "Fault Detection with Multiple Observers", in Proceedings of the IEEE INFOCOM, Florence, Italy, May, 1992.

[2] C. Wang and M. Schwartz, "Fault Detection with Multiple Observers", IEEE/ACM Transactions On Networking, Vol.1, No. 1, Feb. 1993.

[3] C. Wang and M. Schwartz, "Identification of Faulty Links in Dynamic-Routed Networks", to appear in IEEE Journal of Selected Area on Communications, Special Issue on Network Management and Control, 1993.

[4] C. Wang and M. Schwartz, "Fault Diagnosis of Network Connectivity Problems by Probabilistic Reasoning", to be presented at Second IEEE Network Management and Control Workshop, Tarrytown, NY, Sept. 1993.

4. All-optical Networks

We have been working on a two-layered approach to lightwave network design, consisting of (1) determining a logical connection graph (LCG) to satisfy certain prescribed traffic requirements and access station physical constraints, and (2) embedding that LCG into a given physical topology. In the current period we have studied the problem systematically, focussing on reducing the LCG diameter (i.e., the maximum number of hops in the LCG) to a minimum while maximizing the number of stations in the network. The approach taken has been to "cluster" subsets of stations into subnets which are (optically) fully connected, so that stations belonging to the same subnet can reach each other in a single hop. Each subnet containing r stations will require r (r-1) optical connections for full connectivity. To move from one subnet to another requires passing through a (electronic) switch.

It happens that the connectivity diagram for such a structure is nicely modeled as a hypergraph, a direct generalization of a graph. Our work is progressing on algorithms for finding "good" hypergraphs, representing LCG's with small diameter, subject to constraints such as maximum size of an edge, and maximum degree of a vertex. The former parameter corresponds to the maximum size of a fully connected subnet, while the latter parameter corresponds to the maximum number of transmitters/receivers in a network access station. We are focussing on heuristics for designing LCC's taking into account physical constraints in the network, and traffic distributions. We are also developing methods of embedding to conserve the optical resources: fibers and channels.